

PARTICLE DETECTORS

High energy collisions ($p\bar{p}$, pp , e^+e^- , ep , etc.) produce a multitude of particles, charged and neutral.

The "ideal" detector should:

- * detect, track and identify all particles (mass, charge) → (also event vertex)
- * measure momentum/energy, ionization, time of flight etc. with "high" resolution
- * provide full solid angle coverage, fine segmentation (← spatial resolution)
- * have fast response, no dead time.

Practical limitations come from:

Technology & Budget

We need to optimize cost and performance and strike a balance.

So, physics goals of an experiment define what the detector(s) have to do.

- Which final state objects need to be identified with what efficiency and purity?
- What quantities need to be measured with what precision?
- What geometrical acceptances are needed?

Also,
Physics goals impose requirements on the accelerators
beams and beam conditions impose demands on

- read-out electronics (higher rate capability)
- detector dead-time
- space
- radiation-hardness of devices
(those in close proximity of the beam)

Mainly two kinds of HEP experiments

Large-scale General Purpose
CDF, DØ, ALEPH, DELPHI,
L3, OPAL, CMS, ATLAS etc.

Specialized
SLD, Babar,
MiniBoone, MINOS

↓
These also mainly focussing
on high p_T phenomena

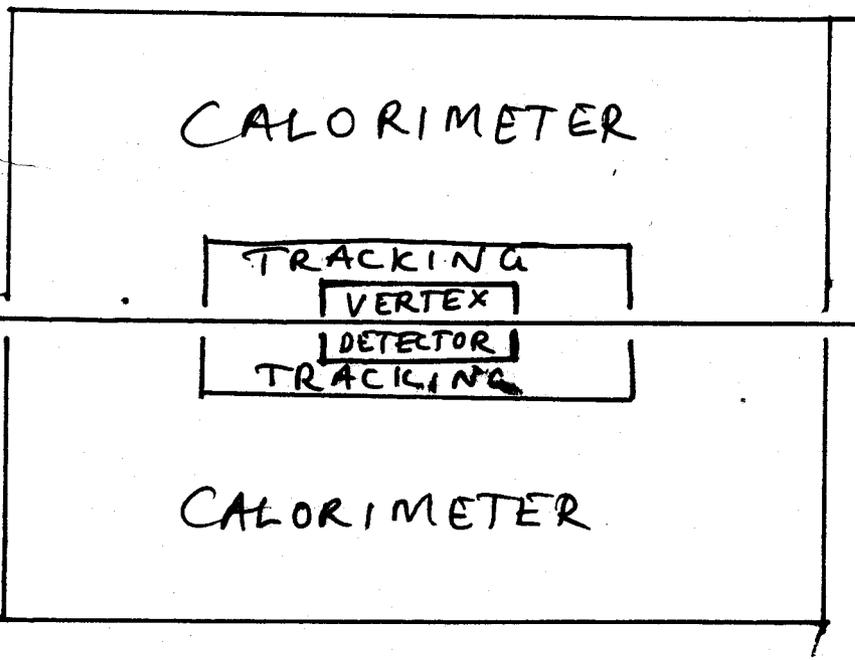
objects we expect to find in high energy collisions:

Various matter particles and gauge bosons
(and particles hitherto undiscovered)

- light quarks as jets
- gluons as jets
- b-quarks as jets with secondary vertex
or soft-lepton signatures
- electrons, muons
- Z 's either as hadronic jets or decaying
leptonically
- photons
- neutrinos with missing energy as the
signature
- all other heavier unstable particles (W, Z, t, \dots)
decaying to aforesaid familiar particles

Generic Collider Detector

MUON SYSTEM



MUON SYSTEM

Tracking with Gaseous Ionization Detectors

We have learnt that ionization is one of the important ways in which charged particles lose energy in matter.

Recall that total ionization of a given thickness of gas for a MIP is

$$n_t = \frac{1}{W} \cdot \frac{dE}{dx}$$

For a mixture of gases (with component fractions f_i)

$$n_t = \sum_i \frac{1}{W_i} \cdot \frac{dE}{dx} \cdot f_i$$

Gas	Z	A	W_i (eV)	$\frac{dE}{dx}$ [keV/cm]	n_p [1/cm]	n_t [1/cm]
He	2	4	41	0.32	5.9	7.8
Ar	18	39.9	26	2.44	29.4	94
Xe	54	131.3	22	6.76	44	307
CO ₂	22	44	33	3.01	34	91
CH ₄	10	16	28	1.48	16	53
CF ₄	42	88	54	5.40	51	100

Example:

For Run I Muon System (PDTs)

we used Ar (90%) / CF₄ (5%) / CO₂ (5%)

$$n_p \approx 31/\text{cm} \quad n_t = 94/\text{cm}$$

Average distance between primary interactions

$$= \frac{10,000 \mu\text{m}}{31} \approx 323 \mu\text{m}$$

Each primary interaction produces ~ 3 secondary interactions

Run II gas mixture:

Ar (80%) CF₄ (10%) CH₄ (10%)

$$n_p \approx 29/\text{cm} \quad n_t = 91/\text{cm}$$

Drift and Diffusion in Gases

Electrons and ions produced in an ionization process will lose their energy by multiple collisions with atoms and molecules in the gas. They approach the thermal energy distributions with average energy,

$$\mathcal{E} = \frac{3}{2} kT \quad \left(\begin{array}{l} k = \text{Boltzmann constant} \\ T = \text{temperature in } ^\circ\text{K} \end{array} \right)$$

$$\approx 40 \text{ meV at RT.}$$

(Equipartition law)

The distribution of kinetic energies will follow Maxwell-Boltzmann distribution,

$$F(\mathcal{E}) = c \cdot \sqrt{\mathcal{E}} e^{-\mathcal{E}/kT}$$

The charges/ions diffuse through the gas by multiple collisions with a Gaussian differential density distribution.

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} \cdot e^{-x^2/4Dt} \cdot dx$$

↙ fraction of the charge found in elemental length dx at a distance x from the origin and after time t .

$D =$ Diffusion coefficient.

The Standard deviation

$$\sigma_x = \sqrt{2Dt}$$

The Diffusion coefficient, D depends on the thermal velocity 'u' of the charged particles

$$D \uparrow \text{ if } u \uparrow$$

$$u = \sqrt{3kT/m}$$

$\therefore D$ decreases with increasing mass of the particles, as expected.

The average mean free path in the diffusion process

$$\lambda = \frac{1}{N \cdot \sigma(\epsilon)}$$

$$\text{where } N = \frac{N_A}{A} \cdot \rho$$

(N_A = Avogadro Number

A = Molar mass

ρ = density of the gas)

$\sigma(\epsilon)$ is the collision cross-section.

$$\lambda_e \gg \lambda_{ion}$$

If the charge carriers are subject to an electric field, then an orderly drift along the field is superposed over the statistically disordered diffusion.

In an electric field of strength E , the drift velocity v_D :

$$v_D \propto E; \text{ also } v_D \propto \frac{1}{p} \quad (p = \text{gas pressure})$$

$$v_D = \mu \cdot E \cdot \frac{p_0}{p} \quad (p_0 = 760 \text{ Torr i.e., Standard Pressure})$$

μ = mobility of the ions

For a mixture of gases, for a given type of ion,

$$\frac{1}{\mu} = \sum_{k=1}^n \frac{C_k}{\mu_k} \quad (C_k = \text{concentration of gas } k, \mu_k = \text{mobility of ion in gas } k)$$

gas	$\lambda_{\text{ion}} (\text{cm})$	$D_{\text{ion}} (\text{cm}^2/\text{s})$	$\mu_{\text{ion}} \left(\frac{\text{cm}^2/\text{s}}{\sqrt{\text{cm}}} \right)$
H ₂	1.8×10^{-5}	0.34	13.0
He	2.8×10^{-5}	0.26	10.2
Ar	1.0×10^{-5}	0.04	1.7
O ₂	1.0×10^{-5}	0.06	2.2

Electrons, because of their small mass, can gain substantial amounts of energy in an electric field between collisions (their mean free paths are large). The mobilities of electrons in gases are about three orders of magnitude larger than that for ions. Electron mobility is not a constant, but depends on electron energy, electric field and the gas composition.

Mean electron energy E_k is much larger in Ar than in e.g., CH_4 or CO_2 .

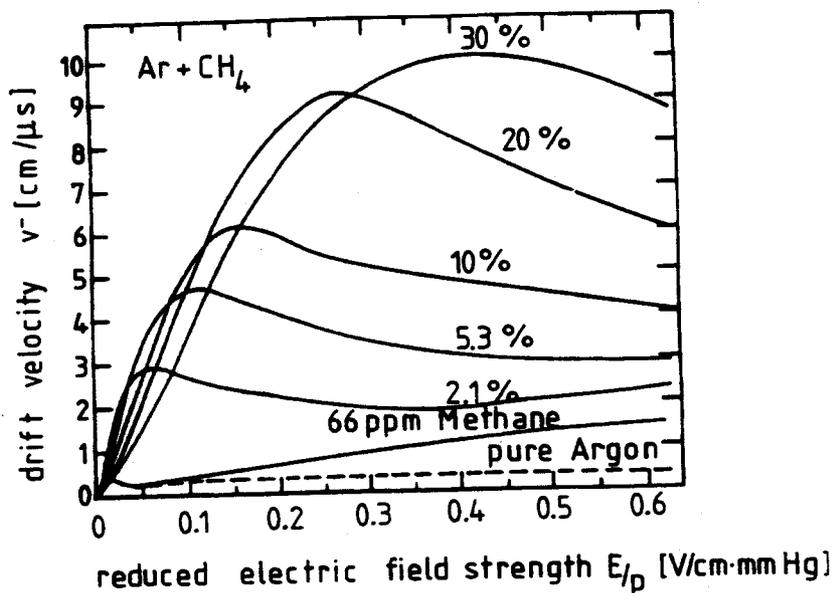
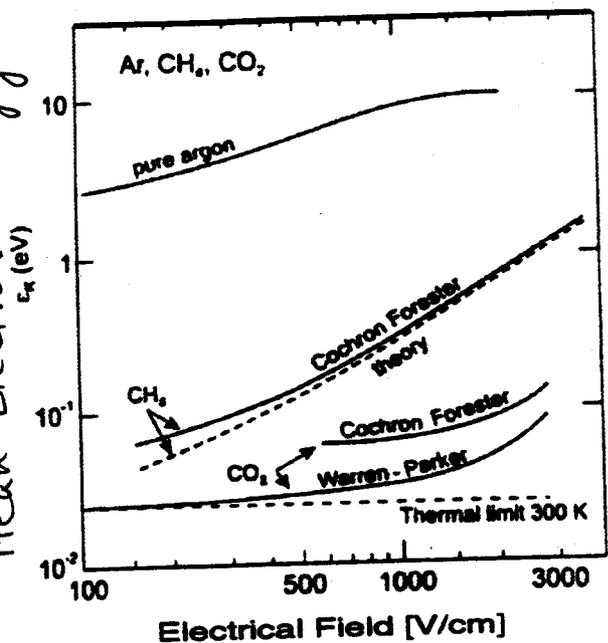
Because 1st excitation level of Ar is at 11.6 eV

1st excitation level in CH_4 is at 0.03 eV (molecular rotational and vibrational levels).

∴ Much more energy is needed to ionize/excite Ar gas than CH_4 or CO_2

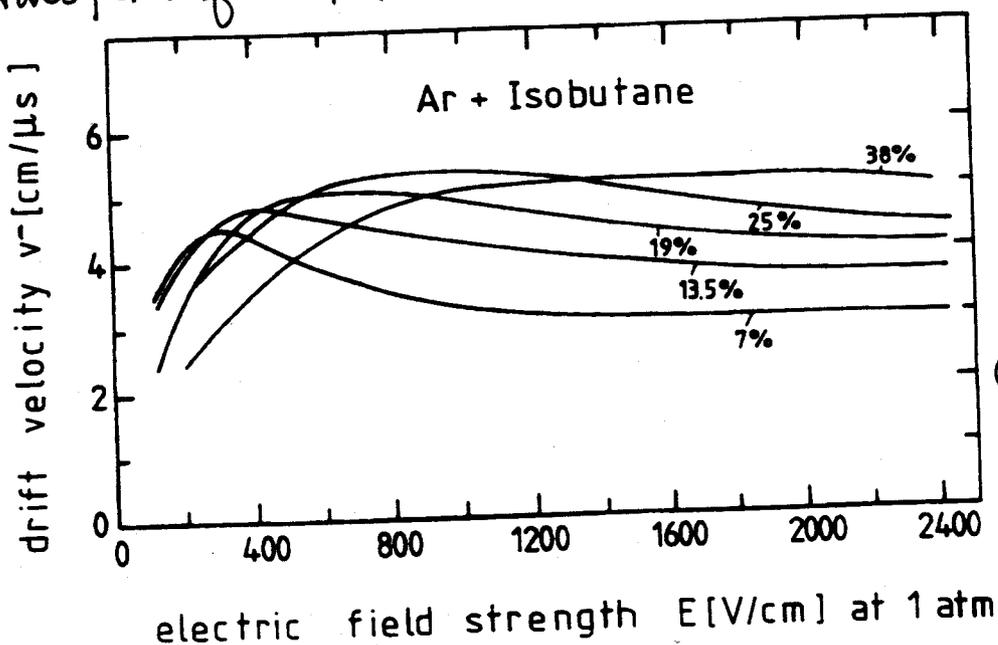
∴ Ar is called a 'hot' gas
 CH_4 and CO_2 are 'cold' gases

∴ Addition of small amounts of cold gas to a hot gas can alter the drift properties of a gas mixture drastically.



Adding small amounts of 'cold' gas to a 'hot' gas like Ar increases the drift velocity.

There are also unwanted effects of admixtures. 1% of air admixture in Ar will remove 33% of migrating electrons/cm of drift! (This is because of molecules that have electron affinity).



So gas lighter of the charge needed. (e affinity large for H_2O and O_2 , negligible in N_2)

Diffusion of electrons result in longitudinal and transverse broadening ← accuracy of position determination is reduced.

We had

$$\sigma_x = \sqrt{2Dt} = \sqrt{\frac{2Dx}{v_d}}$$

$$= \sqrt{\frac{2kT}{eE}} \cdot \sqrt{x}$$

σ_x is much larger for hot gases than for cold gases which are therefore preferred at high values of electric field.

GAS AMPLIFICATION

The simplest gaseous tracking detector is a parallel plate chamber

If one chooses $E = U_0/d$ such that no secondary ionization occurs, and all primary ionization is collected on the electrodes, the device is called an "Ionization Chamber."

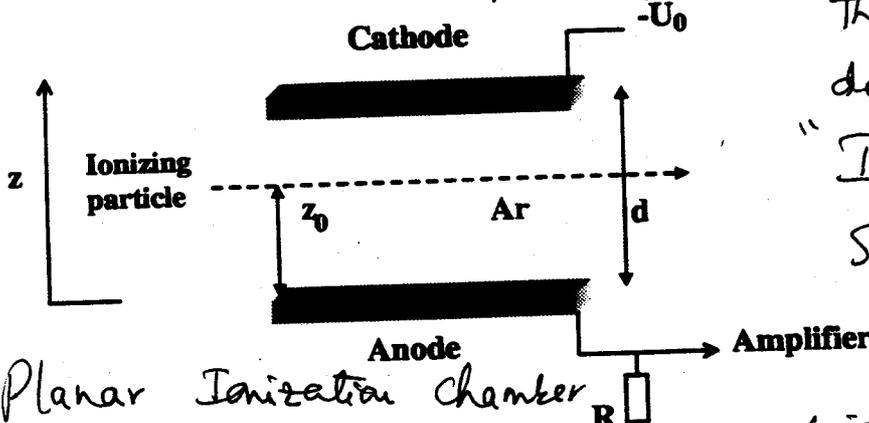
The electrodes, the device is called an "Ionization Chamber."

Signal collected:

$$V = \frac{Ne}{C}$$

with $N \approx 100$, $C = 10 \text{ pF}$,

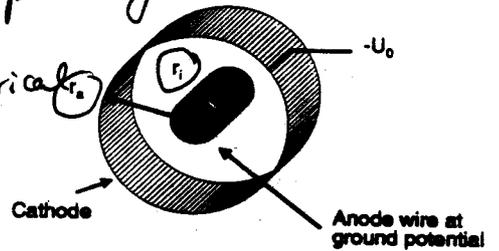
$$V \approx 2 \mu\text{V}$$



Planar Ionization Chamber

As voltage is increased, more and more electrons become energetic enough to produce secondary ionization (avalanche) but, the detected signal becomes dependent on the avalanche length and hence the position of the primary ionization.

This is avoided by using a cylindrical chamber.

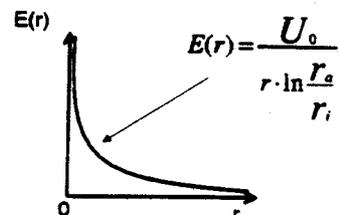


Here
$$E(r) = \frac{U_0}{r \ln\left(\frac{r_c}{r_i}\right)}$$

From Laplace equation in cylindrical coordinates and azimuthal symmetry

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial V}{\partial r} \right) = 0$$

Integrate with constraints $V=0 @ r=r_c$; $V=U_0 @ r=r_i$



Cylindrical chamber

Gain Voltage characteristic for Ionization Counters

- At very low voltages, charges begin to be collected but recombination is still dominant (region A)
- At higher voltages (B) full collection of primary ionization begins. No amplification

← Ionization chamber

- Region C: Avalanche multiplication occurs.

Detected charge: $Q_{det} = G \cdot Q_{deposited}$ where $G = \text{Gain}$

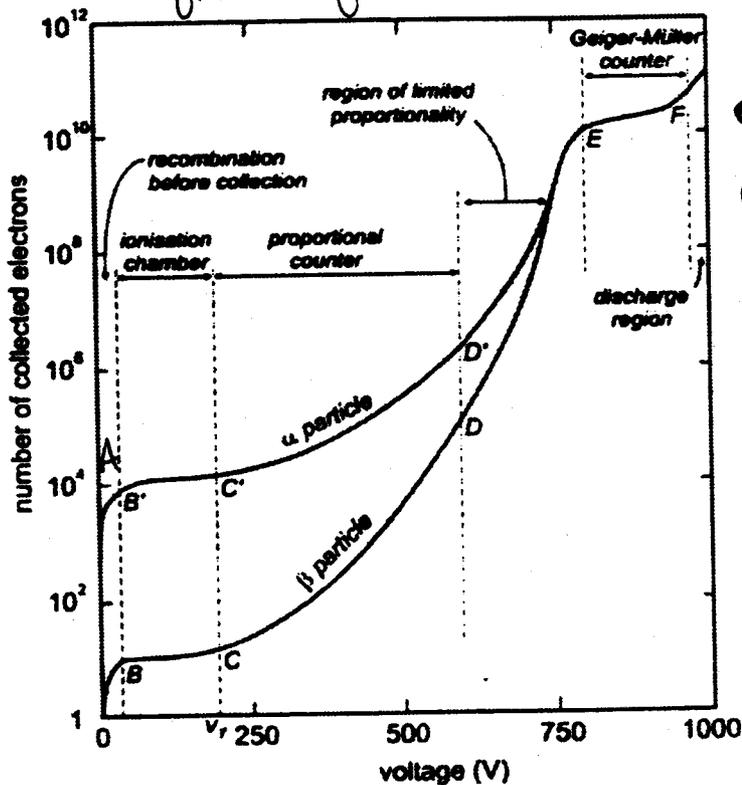
← 'Proportional Counter' region

'G' depends on applied voltage (exponential), and on gas composition, temperature & pressure.

1% change in voltage \Rightarrow 15% change in Gain

- Even higher voltage (D): Proportionality lost due to the space charge build up around the anode wire, screening the field for electrons moving to the cathode

← region of limited proportionality



- E - F: Gain saturates. Generated signal is independent of the original ionizing event.

← Geiger - Muller Counter

- Beyond F, the counter discharges.